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Peter S. Shawhan, for the LIGO Scientific Collaboration and Virgo Collaboration, “Rapid alerts for following up gravitational wave event candidates”, Observatory Operations: Strategies, Processes, and Systems IV, Alison B. Peck, Robert L. Seaman, Fernando Comeron, Editors, Proc. SPIE 8448, 844825 (2012).

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DOI: To be assigned

Rapid alerts for following up gravitational wave event candidates

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ABSTRACT

Gravitational waves carry unique information about high-energy astrophysical events such as the inspiral and merger of neutron stars and black holes, core collapse in massive stars, and other sources. Large gravitational wave (GW) detectors utilizing exquisitely sensitive laser interferometry—namely, LIGO in the United States and GEO 600 and Virgo in Europe—have been successfully operated in recent years and are currently being upgraded to greatly improve their sensitivities. Many signals are expected to be detected in the coming decade. Simultaneous observing with the network of GW detectors enables us to identify and localize event candidates on the sky with modest precision, opening up the possibility of capturing optical transients or other electromagnetic counterparts to confirm an event and obtain complementary information about it. We developed and implemented the first complete low-latency GW data analysis and alert system in 2009–10 and used it to send alerts to several observing partners; the system design and some lessons learned are briefly described. We discuss several operational considerations and design choices for improving this scientific capability for future observations.

Keywords: Gravitational waves, LIGO, Virgo, GEO 600, multi-messenger, time-domain astronomy, afterglow

1. INTRODUCTION

The direct detection of gravitational waves has long been heralded as a new observational tool for astronomy and astrophysics. Indeed, strong gravitational waves are surely emitted by binary systems of neutron stars and/or black holes in close orbits, as already confirmed indirectly by radio observations of pulsars in a few such systems in our galaxy.^{1–3} Ground-based gravitational wave (GW) detectors can directly detect signals from the final seconds to minutes of “inspiral” leading up to the merger of a binary system.^{4,5} Short-duration GW signals are also expected to be emitted from the collapsing cores of massive stars^{6,7} and from perturbed neutron stars and black holes,⁸ although the dominant excitation and emission mechanisms—and thus the strength of the waves—are much less clear. GW transients might even be produced by cosmic strings⁹ or other exotic sources.

Ground-based detectors are also seeking continuous signals from non-axisymmetric spinning neutron stars^{10–12} and stochastic GW background radiation,^{13,14} while pulsar timing campaigns^{15–17} are currently monitoring selected stable pulsars to pick out the signatures of very-low-frequency GWs from supermassive black hole binaries and other sources. Someday, hopefully, space-based interferometers similar to LISA¹⁸ will be launched to study the intermediate frequency band and the galactic and extragalactic GW sources that populate it.¹⁹

While GWs still have not yet been directly detected, the detectors operated up to this point have successfully collected data which have been analyzed to set ever-improving upper limits on the rates and strength of likely GW signals (such as Refs. 20 and 21). Major upgrades currently underway should finally enable the detection of GW events later this decade, and the GW science community is now preparing to take full advantage of the new capabilities. This presents an excellent opportunity for GW scientists and astronomers to collaborate to obtain multi-messenger observations of transient events through their electromagnetic (EM) as well as GW emissions, regardless of which messenger first detects a given event. The purpose of this article is to discuss the prospects for EM follow-up observations triggered by the rapid identification of GW event candidates. First steps in that direction have already been taken, and a broader future program is now being planned.

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2. THE GRAVITATIONAL WAVE DETECTOR NETWORK

Direct detection of gravitational waves was first attempted using resonant “bar” detectors^{22,23}—and the AURIGA²⁴ and NAUTILUS²⁵ cryogenic bar detectors are still operating—but the past two decades have seen the rise of large-scale laser interferometers which achieve better sensitivity and span a much wider frequency range. The basic detection principle is simple: a laser beam is split into two beams which travel along perpendicular “arms” with mirrors at the ends, and interference when the reflected beams are recombined indicates the minute differential changes in the effective lengths of the arms produced by a passing gravitational wave. But the remarkably small amplitude of the GWs reaching Earth, with a strain (fractional length change) of order 10^{-21} or less, demands exquisite stability and control of the laser and optical systems, mirror positioning and alignment, low-loss optical components, careful management of sensor and actuator noise, and nearly total isolation from ground vibrations and other environmental disturbances.

Gravitational-wave “observatories” with kilometer-scale interferometric detectors have been built and operated in the United States (LIGO) and Europe (GEO 600 and Virgo), as described below. Medium-scale prototypes have also been developed in Japan as a prelude to building a large detector. As these are effectively quadrupole antennas, each detector has nonzero response to GWs arriving from almost all directions, with direction- and polarization-dependent “antenna factors” between 0 and 1; and because GWs pass through the Earth unimpeded, *all* operating detectors generally will respond to the same incoming wave. Allowing for direction-dependent arrival time differences, the GW detectors can be used together as a coherent network with multiple baselines. Recognizing this fact, the collaborations operating the different detectors have agreed to combine and jointly analyze all of the data, and this cooperative philosophy is expected to continue into the future.

As of this writing in mid-2012, the field is in the midst of a major transition, as the first-generation detectors (briefly summarized below) have ceased operating and new “advanced” detectors are being constructed in their places. We will again have a true network of GW detectors operating later this decade, with roughly an order of magnitude greater amplitude sensitivity than in the past.

2.1 First-generation detectors

The LIGO project^{26,27} has built two observatories—on the Hanford reservation in Washington and in Livingston Parish, Louisiana—and has operated *three* detectors simultaneously: the LIGO Hanford Observatory housed interferometers with 4-km and 2-km arms, sharing a vacuum envelope, while LIGO Livingston has had a 4-km interferometer matching the longer one at Hanford. LIGO is primarily funded by the U.S. National Science Foundation (NSF) through the “LIGO Laboratory” at Caltech and MIT, but the science mission of LIGO is carried out by a much larger organization, the LIGO Scientific Collaboration (LSC), which includes hundreds of scientists from the U.S., Europe and elsewhere. LIGO detector installation began in 1998 and a series of short “science runs” began in 2002, albeit with limited sensitivity. After further commissioning, the LIGO detectors reached their design sensitivity goal in 2005 and recorded data in the “S5” science run from 2005–7.²⁷ With some enhancements (testing technologies to be used by the advanced detectors described below), LIGO had an S6 science run from 2009–10.

The GEO 600 detector²⁸ (also known simply as GEO) has been built by a collaboration of German and British scientists and is sited near Hannover, Germany. With folded 600-meter arms, GEO is smaller than the other km-scale interferometers but has pioneered more ambitious techniques for interferometry and mirror suspensions that have informed the designs of later detectors. The GEO 600 detector and the scientists who work with it are fully part of the LSC (despite the fact that only LIGO appears in the *name* of the collaboration), and GEO 600 has often collected data in science runs synchronously with LIGO. Additionally, the GEO team generally tries to operate the detector and record data whenever it is not being actively upgraded or commissioned, in an “AstroWatch” mode to be prepared for any remarkable event such as a supernova in our galaxy.

Virgo²⁹ is a 3-km detector located in Cascina near Pisa, Italy with a design generally similar to LIGO’s. Begun as a French-Italian project funded by the Centre National de la Recherche Scientifique (CNRS) and the Istituto Nazionale di Fisica Nucleare (INFN) through forming the European Gravitational Observatory (EGO) consortium, the Virgo Collaboration now includes researchers from other European countries as well. The Virgo

detector reached a scientifically significant sensitivity level in 2007 and carried out its first science run, VSR1, together with the last 5 months of the LIGO/GEO S5 run, enabling the first LIGO-Virgo joint analyses.^{30–33} The next two science runs, VSR2 and VSR3, were synchronous with the S6 run; a VSR4 run followed after further commissioning of the new set of mirrors installed between VSR2 and VSR3.

2.2 Advanced gravitational wave detectors

GEO is arguably the first “advanced” GW detector, with a number of recent and planned technological improvements³⁴ in laser power, signal recycling, and the use of “squeezed light” to push below the normal quantum shot-noise level.³⁵ This program of upgrades is called “GEO-HF” since the main focus is on high frequencies, above several hundred Hz. GEO is currently collecting data in AstroWatch mode with an uptime of about 70%. However, GEO’s relatively high noise at low frequencies means that it has rather limited sensitivity for binary inspirals and other low-frequency sources. A major step forward will come later this decade with the completion of the Advanced LIGO and Advanced Virgo upgrades, and the construction of the KAGRA detector in Japan.

Advanced LIGO³⁶ is a nearly total replacement of the instrumentation at the LIGO observatories with higher-power lasers, larger mirrors, a dual recycling optical configuration with stable recycling cavities, multi-stage passive and active mirror suspension systems, and new control and readout electronics. These changes are designed to reduce the limiting noise contributions over the entire frequency band by an order of magnitude compared to the initial LIGO detectors, as well as extending downward to ~ 10 Hz. The use of squeezed light is being studied as a possible enhancement. Components are currently being assembled and tested for three detectors, all 4 km long. The original plan was to install two detectors at Hanford and one at Livingston, but there is now a fully developed proposal to install one of the detectors at a new observatory to be built in India, which will form additional long baselines and greatly improve the ability of the network to localize sources in the sky. The first two detectors, at Livingston and Hanford, should be fully installed by the end of 2013 and basically operational by 2014; following initial commissioning, a first science run is likely in 2015. After further commissioning and tuning, the detectors should reach their design sensitivity levels a few years later. Assuming that the LIGO-India plan is approved by the U.S. National Science Board and that Indian funding for the new observatory is confirmed, the third detector will be installed at the Indian site late this decade and should be ready to start collecting science data around 2020.

The Advanced Virgo³⁷ design is similar to Advanced LIGO and involves many of the same kinds of upgrades, including higher laser power, larger mirrors, and dual recycling. The existing Virgo “superattenuator” mirror suspensions,³⁸ with multiple passive stages, will continue to provide sufficient isolation from seismic noise. An Advanced Virgo Technical Design Report has been completed, and detailed planning and scheduling are now underway. The goal is to have a robustly operating detector in 2015 and to begin collecting science data as soon as possible after that.

Funding for the Japanese KAGRA detector,³⁹ formerly known as the Large-scale Cryogenic Gravitational-wave Telescope (LCGT), was approved in 2010. It will have 3-km arms and a dual-recycled optical configuration similar to Advanced LIGO and Virgo. Uniquely, KAGRA will be located underground, in the Kamioka mine in western Japan, where seismic noise and gravity gradient noise are much lower than at the surface. It will also have sapphire mirrors cooled to 20 K to reduce thermal noise, as has been demonstrated with the CLIO 100-meter cryogenic prototype.⁴⁰ An initial 3-km room-temperature interferometer without recycling is expected to be operational by 2015, with the full cryogenic interferometer ready to start taking data by 2018.

Thus, within ~ 3 years we should have two or three advanced detectors collecting data with significantly better sensitivities than the past network, with full design sensitivity and KAGRA following a few years after that, and LIGO-India somewhat later; see Fig. 1. The advanced detectors will be capable of detecting signals in a volume of space ~ 1000 times larger than the initial detectors. It has been estimated that the Advanced LIGO and Virgo detectors will likely detect a few dozen binary merger events per year;⁴¹ although such estimates have large uncertainties and the expectations for other event types are even less well known, they motivate us to prepare now for a comprehensive science program—and one that is not restricted to the GW signals alone.



Figure 1. Locations of current and future kilometer-scale gravitational wave detectors. The GEO 600 detector is currently taking data; the Advanced LIGO detectors at Hanford and Livingston and Advanced Virgo are expected to begin taking data in 2015; KAGRA should operate in its full optical configuration starting around 2018; and LIGO-India around 2020. LIGO-India is contingent on final approvals and funding, and its exact location has not yet been determined.

3. CONNECTING WITH OTHER OBSERVATORIES

The most likely sources of detectable gravitational waves are all highly energetic events; for example, the inspiral and merger of two neutron stars releases $\simeq 5 \times 10^{53}$ erg of gravitational binding energy. While most of that energy is emitted in the form of neutrinos and gravitational waves,⁴² a fraction of it can go into electromagnetic radiation. In fact, it is believed that binary mergers are the progenitors of most short-hard gamma-ray bursts (GRBs) (see, for example, Refs. 43 and 44), with multiple observational features supporting that hypothesis.^{45, 46} Binary mergers and other types of disruptive events may naturally power EM emissions in the X-ray, optical, and radio bands through various mechanisms.

Even the advanced GW detectors will be limited to the relatively nearby universe by the detector noise floor; maximizing the detection rate for GW events calls for setting event candidate selection thresholds as low as possible while maintaining a very low “background” rate from noise fluctuations. General searches using GW data only must accept a candidate from any time or sky position. *However*, having an observed EM transient counterpart with a consistent time and sky position would greatly increase confidence in a GW event candidate, and could thus be the key supporting evidence that confirms the candidate, even if it was a bit too weak to be cleanly distinguished from the background based on the GW data alone. Furthermore, the EM counterpart may pin down the host galaxy and local environment of the source, while comparison of the EM and GW signals—e.g., relative timing and durations, relative energy release, and polarization content—would provide unique information about the identity and astrophysics of the progenitor. For instance, GW observations should eventually be able to confirm or rule out the binary merger model for short-hard GRBs.

For several years, the LSC and Virgo have been carrying out deeper GW searches around the times and sky positions of many astrophysical “triggers” (reported events) such as GRBs, magnetar flares, and pulsar timing glitches; Refs. 47, 48 and 49 present some recent examples. Triggered GW searches are also in progress using high-energy neutrino candidates and nearby supernovae as targets. Such searches are typically about a factor of 1.5 to 2 more sensitive than all-sky (un-triggered) GW searches, meaning that sources can be detected up to twice as far away, extending the science reach significantly.

Still, to gain the most from associating GW and EM events, we must consider that not all EM transient events will be detected promptly—if at all. Excellent sky coverage is now available in gamma rays and hard X-rays thanks to the Gamma-ray Burst Monitor (GBM)⁵⁰ on the Fermi spacecraft, which views all of the sky not occulted by the Earth, together with the Interplanetary Network (IPN) of gamma-ray instruments on several spacecraft,⁵¹ which see the whole sky but with lesser sensitivity. However, GRBs are understood to be strongly beamed (see, for example, Ref. 52), so only a small fraction of their progenitors can actually be observed via gamma-rays. Systems which launch gamma-rays somewhat off-axis to the line of sight, or

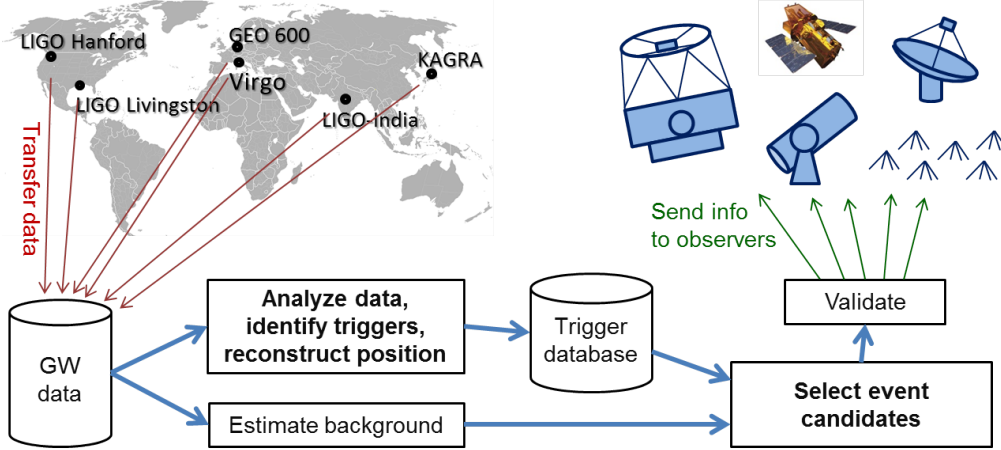


Figure 2. Main steps in processing data from the GW detector network and rapidly generating alerts for follow-up observations. (*Swift* image credit: NASA E/PO, Sonoma State University, Aurore Simonnet.)

which produce only moderately relativistic jets (“failed GRBs”), may still be detectable in the optical or radio bands as “orphan afterglows”.^{53,54} Neutron star mergers are likely to also produce fainter, isotropic “kilonova” light curves in the optical band which are powered by the radioactive decay of elements produced by *r*-process nucleosynthesis.⁵⁵ Because only a small fraction of the sky is viewed at any given time by sensitive optical and radio instruments, these transient signatures would only be caught serendipitously—*unless* gravitational wave (or high-energy neutrino) detectors can identify these events promptly and accurately enough to tell telescopes where to point.

Data from the GW detector network can, in fact, be analyzed within minutes to identify candidate events and reconstruct a sky map of the likely position of each candidate. This information can then be passed to astronomers for follow-up imaging. (The general strategy is sometimes called “LOOC-UP” after an early pilot study.⁵⁶) We developed and tested such a system during the 2009–10 LIGO-Virgo joint science runs, and will support and improve this capability for observing with the advanced GW detector network. Below, we discuss the main characteristics of the past system as well as some improvements envisioned for the future.

4. OPERATIONAL CONSIDERATIONS FOR PROMPT FOLLOW-UP OBSERVATIONS

The overall goal is to identify transient events in the GW data quickly, determine their sky positions as well as possible, and communicate that information to observers with access to telescopes for capturing images of the appropriate region(s) in the sky. It is desirable to minimize the latencies of all of those steps so that the telescopes can catch a fading afterglow (if there is one) as early as possible. It should be noted, though, that other types of EM emissions would take some time to appear, such as a kilonova light curve which peaks after ~ 1 day,⁵⁵ or synchrotron emission in the radio band⁵⁷ which would spread over weeks to months. Therefore, rapid alerts can support both rapid and delayed follow-up observations.

For the 2009–10 LIGO-Virgo science run, we implemented a complete mostly-automated data analysis, event selection and alert distribution system, and passed alerts to several partner observers. That system and evaluations of its performance are described in Refs. 58 and 59. Figure 2 shows the main elements and general data flow through the system, illustrated with the future network of advanced GW detectors. In this section we discuss a number of operational considerations based on our experience with the past system, along with some notes about changes envisioned for the future.

4.1 Data collection

First of all, we need to have multiple GW detectors collecting data at the same time with comparable sensitivity, because it is mainly the difference in arrival times which tells us about the sky position of the source. (More

about that in section 4.3.) The 2009–10 follow-up program was active only when both 4-km LIGO detectors and Virgo were all collecting science-mode data. GW detectors can operate day and night, but in practice they do not operate all the time; bad weather conditions (causing elevated seismic noise), occasional nearby human activities, instrumental problems and scheduled maintenance periods all contribute to downtimes that have historically been $\sim 10\text{--}30\%$. Thus, although science runs of the various detectors are carried out synchronously when possible, different subsets of the network will be collecting science-mode data at any given time.

Data from all of the detectors needs to be calibrated quickly and transferred to one or more computer centers to be analyzed together. In 2009–10, calibration took $\sim 15\text{--}20$ s and all of the GW strain data was transferred to the main archive at Caltech and to the Virgo observatory site in less than 1 minute, on average, ready to be analyzed. Data transfer latencies could perhaps be trimmed in the future, although these have not been the limiting factor so far.

4.2 Low-latency analysis

Binary mergers are a natural target for rapid follow-up observations because they are the best predicted GW source type and because there are many models for EM emission at various wavelengths. The GW waveform from the inspiral phase leading up to merger mainly depends on the masses of the two objects and can be calculated accurately, at least for neutron stars and stellar-mass black holes with relatively little spin. This allows the data to be searched using optimal matched filtering with a bank of templates. In 2009–10, the data arriving at the Virgo Cascina site was promptly processed using the MBTA algorithm to search for inspiral signals in the three data streams.⁵⁹ Large output values from the matched filters were recorded as GW “triggers” in a database, along with reconstructed sky position information, within a few minutes.

To allow for other types of events which are not so well modeled (if at all), we also apply GW “burst” search algorithms which are designed to find transient GW signals in the data without making any assumptions about the specific waveform. The basic approach is to test for signals above the baseline noise level with consistent relative times, frequency and polarization content in the multiple data streams. In 2009–10, three different GW burst search algorithms were used in parallel: coherent WaveBurst for arbitrary signals, coherent WaveBurst with a linear polarization constraint, and Omega Pipeline with a Bayesian coherent analysis stage.⁵⁸ These algorithms responded best to different types of GW burst signals, and each was set up to record outliers above a moderate threshold in the trigger database, along with sky position information. This processing typically took about 5 minutes.

Background from noise fluctuations—in other words, the rate of “false alarms”—is a critical consideration for any GW search because very weak signals are being sought, and the statistical properties of the noise are not known *a priori*. The rate and properties of background triggers can be estimated by time-shifting data streams from the different detectors, which removes any correlation from a real GW signal while sampling a different alignment of random fluctuations and/or instrumental glitches (uncorrelated since they are at widely separated sites). Trying many different shifts and re-analyzing an interval of data (or, for the MBTA coincidence analysis, simply multiplying average single-detector trigger rates) yields a background rate estimate with good statistical precision.

The next step is to select highly significant triggers from the (un-shifted) analysis based on how unlikely they are to be random background; this is quantified by an effective false alarm rate (FAR) for the background distribution stronger than the trigger being considered. One difficulty is that the outlier *tail* of the background distribution is crucial for evaluating the most interesting triggers, but measuring that tail requires a considerable quantity of data and/or many different time shifts. With first-generation GW detectors, at least, the background rate and properties change on various time scales; thus there is an issue of deciding how best to estimate the background for a given point in time. In 2009–10, our selection criteria involved multiple background estimates averaged over different time intervals ranging from 10 minutes to several hours.⁵⁸ That worked well enough that we were able to choose “event candidates” to pass along to follow-up observers at approximately the desired average rate, which was ~ 1 observable candidate per week for most partner telescopes and lower for certain others, including the *Swift* XRT and UVOT.⁶⁰

Finally, before sending an alert out to observers, we want to be sure that it is not an obvious instrumental artifact to avoid spending telescope time unnecessarily. During the 2009–10 run, we used a combination of

automatic and manual checks on data quality and current conditions at the detector sites at the time of each event candidate, using the judgment of detector operators and scientists at the sites together with an “EM follow-up expert” who was on shift at the time. About 1/3 of the event candidates were judged to be questionable for some reason and were rejected. This validation step thus improved the “purity” of the rapid alerts to some extent, but it added ~ 10 to 30 minutes to the latency for sending out the alert, dominating the total latency. In the future, we may be able to improve the automated checks to the point where we can remove the manual validation stage and send alerts out more quickly.

4.3 Position reconstruction

Despite having baselines of thousands of kilometers, the GW network is generally not able to reconstruct the sky position of a transient candidate very well because the signals of interest are at low frequency and low signal-to-noise ratio. Position information comes mainly from the difference in arrival times between detector sites, and the resulting position uncertainty can be predicted approximately in terms of the properties of the signal waveform.^{61,62} There is, however, additional information in the relative signal amplitudes since the detectors are oriented differently and therefore have different antenna factors for both GW polarization components. In any case, localizing events well requires data from at least three detectors; with only two detectors, we can still do a good search for GW events using appropriate coincidence tests, but can only crudely localize candidates along a ring on the sky. Having four or more detectors in the future will have the advantage that when one goes down, the others can still localize sources well.

Achievable sky region areas have been studied analytically^{61,62} and using Monte Carlo simulations,^{63,64} and continues to be a topic of interest. It is difficult to summarize the results since they depend strongly on the GW detector network operating at the time as well as the waveform, amplitude and sky position of the GW signal. With the full future network of advanced GW detectors, sky error regions of a few square degrees are predicted (e.g., for binary neutron star inspirals), whereas earlier on with just the Advanced LIGO Hanford, LIGO Livingston and Virgo detectors, error regions should typically be tens of square degrees. It should be noted, though, that these estimates sometimes assume detectors with equal sensitivities, which is unlikely to be the case. Also, real data analysis algorithms which have to deal with non-stationary noise may not attain the ideal performance, and calibration uncertainties can lead to systematic shifts in reconstructed positions. Those issues will need to be addressed carefully to ensure that telescopes can be pointed accurately.

Simple time-of-flight triangulation with three detectors normally picks out two areas of the sky; a fourth detector usually can resolve the ambiguity. The error regions can, however, be rather elongated depending on their position in the sky (see, for example, Fig. 1 of Ref. 62), and that may affect how telescopes will be able to cover them. Furthermore, coherent reconstruction of arbitrary burst signals often produces multiple disconnected regions (e.g., Fig. 3 of Ref. 58) as features in the data stream line up differently. The end result in either case is a “sky map” representing the estimated probability of the source being at each position.

Because sky maps may span large areas that are impractical to cover with most telescopes, the 2009–10 follow-up campaign made the additional assumption that sources were expected to be in nearby galaxies or in Milky Way globular clusters. That is, a catalog of nearby galaxies (and globular clusters) was used to weight the sky maps and guess the most likely host galaxies based on distance and luminosity; those were then imaged. Monte Carlo simulations indicated that this approach would significantly improve the chance of imaging the correct source location,⁵⁸ though that conclusion was model-dependent. It is not clear whether a galaxy-targeting strategy will still be useful in the future when the GW detector network will be reach out to greater distances, encompassing a much larger number of galaxies per unit solid angle, and where current galaxy catalogs are much less complete. It is also not clear that we should expect all sources to be found in galaxies.⁴⁶

4.4 Communication with follow-up observers

After selecting (and validating) an event candidate, the essential information about the candidate includes the arrival time of the GW signal at the Earth, a measure of its significance or FAR, and a sky map describing its apparent location. The type of signal (e.g., binary merger vs. burst) and some parameters such as component masses or burst frequency and duration may also influence the observing strategy, if they can be determined reasonably accurately from the GW data. For the 2009–10 run, the LSC and Virgo used the sky map and galaxy

catalog to select (RA,Dec) coordinates for the telescopes to point at, but in the future we expect to provide the full sky map to observers.

The 2009–10 follow-up observing campaign was organized in a relatively short period of time and involved ten partner groups, each using one or more telescopes. Communication protocols were adapted to each partner’s existing telescope scheduling system, with the result that eight different protocols or interfaces were used—although most were based on either the GCN⁶⁵ notice binary packet format or the VOEvent⁶⁶ format. Future operations will benefit greatly from distributing alerts through one or two standard infrastructures that are widely used by the transient astronomy community at that time, such as GCN/TAN or VOEventNet.⁶⁷ One consideration is that after the initial rapid alert, revised information may become available later—such as a refined sky map, physical parameters of the apparent source system, and/or an updated assessment of the significance of the event candidate—which should be distributed and may influence further follow-up observations.

4.5 Impact of follow-up observations

The findings of follow-up observations for a given GW candidate, combined with the original GW data, can hopefully answer the questions: Is this event real? Where is it? What is the source? Finding a plausible EM transient counterpart should add confidence, and in some cases may make the difference between a marginal candidate and a firmly established astronomical event. However, given the large sky areas associated with the GW candidate, it is important to recognize that false associations with unrelated EM transients are quite possible, even likely. It will be essential to classify transients (e.g., by following light curves or with spectroscopy) to minimize false associations with unrelated events, and to understand the effectiveness of that classification for a broad range of transients, in order to get some handle on the “false association probability”. That will directly affect how much additional confidence the counterpart provides.

Finally, rapid feedback from observers when a firm or possible EM counterpart is found will be valuable for the GW analysis of the event as well as for obtaining further EM observations. It will likely lead to deeper investigation of GW data quality and a re-assessment of the confidence in the event. And, by pinning down a more precise sky location and/or estimated distance, it can enable improved estimates of other parameters of the system from the GW data, such as the masses and orbital inclination of the compact binary progenitor system, which would sharpen the emerging picture of the event.

5. SUMMARY: PROSPECTS FOR MULTI-MESSENGER SCIENCE

An advanced gravitational wave detector network is currently under construction and should be operational around the middle of this decade. We are preparing now to be able to rapidly analyze the data and issue alerts for significant GW event candidates within a few tens of minutes or less, using lessons learned from our first attempt in 2009–10. Once the first two LIGO detectors and the Virgo detector are operating with comparable sensitivity, we should be able to provide sky maps for some candidates with typical areas of tens of square degrees, although that area depends strongly on the signal type, strength, and sky location. Full LIGO/Virgo detector sensitivity and additional detectors will follow later on and will greatly improve the rate of detected events and their localization.

The LSC and Virgo are committed to providing rapid alerts to astronomers interested in following up GW event candidates. A policy document⁶⁸ posted this year outlines the general philosophy; the details of how best to implement the plan are currently being worked out. As described in the policy, during the initial science run(s) (while the detectors are still being commissioned), candidates will be shared with partners through memoranda of understanding intended to ensure coordination and confidentiality of information during the time when any public announcements about the first direct detection(s) of gravitational waves will need to be carefully vetted. After 4 GW events have been published, we will begin releasing highly significant triggers promptly to the public, while partners will continue to have access to larger data sets for more systematic follow-up campaigns.

The next several years will be an exciting time for doing science with gravitational waves *and* well-established EM observing. The relatively large sky areas involved call for strategic planning and appropriate observing resources in order to find the counterparts and rule out false associations, but there is a huge potential payoff in connecting the complementary signals, which should teach us much about energetic astrophysical events.

ACKNOWLEDGMENTS

The corresponding author is grateful for the support of the U.S. National Science Foundation through grant PHY-1068549. The authors gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory, the Science and Technology Facilities Council of the United Kingdom, the Max-Planck-Society, and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector, and the Italian Istituto Nazionale di Fisica Nucleare and the French Centre National de la Recherche Scientifique for the construction and operation of the Virgo detector. The authors also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the International Science Linkages program of the Commonwealth of Australia, the Council of Scientific and Industrial Research of India, the Istituto Nazionale di Fisica Nucleare of Italy, the Spanish Ministerio de Economía y Competitividad, the Conselleria d'Economia Hisenda i Innovació of the Govern de les Illes Balears, the Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientific Research, the Polish Ministry of Science and Higher Education, the FOCUS Programme of Foundation for Polish Science, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the National Aeronautics and Space Administration, the Carnegie Trust, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation.

This paper has been assigned the identifier ligo-p1200070-v2.

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